IGPP PROGRESS REPORT-FY04

Project Title: Behavior of Th and Sm in planetary surface and magmatic environments. Extending remotely sensed chemical data to better understand planetary evolution.

Principal Investigators/ Affiliations: Charles K. Shearer (Institute of Meteoritics, UNM).

Other Investigators/ Affiliations: David T. Vaniman (Los Alamos National Laboratory).

Students/ Affiliations/ Postdocs: Justin J. Hagerty (Institute of Meteoritics, UNM).

Summary of Objectives, Results, Conclusions

Task 1. Th-Sm heterogeneities in the lunar mantle as reflected in primary lunar basalts.

Lunar picritic glasses represent magmas that are close approximations of primary lunar melts. These glasses are ideal for investigating the behavior of Th and Sm in primary basaltic magmas and the lunar mantle because of their primitive compositions. Analysis of Th and Sm in these glasses by ion microprobe is a fundamental step for extending remotely sensed data to decipher volcanism on a planetary scale. The Sm/Th of the picritic glasses approximates the Sm/Th of the sources for these magmas and can therefore be used to infer compositions of Sm/Th in the lunar mantle.

Task 2. Behavior of Th-Sm during basalt crystallization. Study of the Makaopuhi lava lake.

The Makaopuhi lava lake provides a unique natural laboratory in which to study the cooling and crystallization of basaltic magmas. During the crystallization of the lava lake, direct measurements of thermal history, oxygen fugacity, volatile content, petrography-chemistry, viscosity, and density were made. Individual phases (glass, olivine, pyroxene, and plagioclase) in samples from the lava lake will be analyzed for Th and REE by secondary ion mass spectrometry to reconstruct the relationships among the behavior of these elements, melt characteristics, and system dynamics. This task will allow us to carefully measure the behavior of Th and Sm in a closed and simple magmatic system where the principle controls on Th-Sm fractionation can be determined and then applied to other basaltic systems.

Task 3. Behavior of Th-Sm during regolith evolution.

The assumption for remotely sensed geochemical data from the Moon is that the mineralogical and geochemical characteristics of the regolith reflect the underlying bedrock lithologies. The regolith, however, consists of a wide variety of components that have undergone modification at the lunar surface. Because orbital data are obtained on regolith and not rocks, an understanding of regolith processes is crucial to the interpretation of orbital geochemical mapping. Volcanic regolith glasses can provide the broadest sampling and thus the most direct basis for comparison with the orbital data. In-situ ion microprobe analyses will be made on these glasses in order to analyze Th and REE distributions. This will provide a better understanding of the behavior of Th and REE during regolith evolution, providing tremendous leverage to the correlation of local surface and global orbital data. These data will be compared with previously made observations of mineral modes making up distinct grain sizes to evaluate the potential extent of Th-Sm fractionation in lunar lithologies.

Report

I. Introduction (background and approach)

Remotely sensed geochemical data provide extremely valuable information concerning the global distribution of elements on a planetary surface. However, it is difficult to extend these data to a quantitative understanding of a planet's interior because of bedrock cover by planetary regolith and an overall lack of quantitative understanding of how selected elements may behave during magmatic and surface evolution. Fortunately, samples such as basalts provide a wealth of information about the composition and evolution of the crust, mantle, and core of a given planetary body. In essence, basalts can act as "ground truth" for the remotely sensed data allowing maximum content extraction from the remotely sensed data.

Several elements such as Th, rare earth elements (REE), and Fe can be measured easily and accurately by both the remote sensing and in-situ analysis communities. We therefore proposed a study using both analytical methods to yield valuable information on the behavior of Th (relative to Sm and Fe) during magmatic and regolith evolution. This can be accomplished by determining the compositional range of primary basalts that the lunar mantle can produce, by documenting the behavior of Th, Sm, and Sm/Th during the crystallization of an extremely well documented basaltic system, and by documenting the behavior of Th and Sm in lunar regolith components.

Three sample suites have been used in this study: (1) lunar glasses from the Apollo 11, 12, 14, 15, and 17 landing sites, (2) core samples from the Makaopuhi lava lake that was drilled by the USGS, and (3) mare regolith samples from the Apollo sites. Trace element analyses of Sm and Th in glasses and minerals have been conducted using the Cameca 4f ims that is located in the Institute of Meteoritics at the University of New Mexico. Conditions for the analysis of Th and Sm are as follows: 10kV O^- primary beam, beam current 15nA with a beam diameter of 15 microns, energy offset voltage of 75 V and an energy window of ±25 V. Analyses of high precision and accuracy for Th and Sm are accomplished using up to six standards for each element. The standards have elemental compositions that bracket the concentration range observed in the unknowns. Calibration curves for the Th and Sm are constructed from the relationship between $(I_{Th,Sm}/I_{Si}) \times SiO_2$ and concentration of Th or Sm in the standards.

II. Progress During the Reporting Period

A. Major Findings

1. The variability of Th concentrations and Sm/Th ratios observed in the lunar volcanic glasses indicates that there are distinct reservoirs with various enrichments and fractionations of both Th and Sm. The source regions for the Apollo 15 green glasses, representing early lunar magma ocean (LMO) cumulates, have calculated Th and U concentrations substantially lower than the bulk Moon. The data from the pyroclastic glasses also indicate that there may be mixing between early cumulate sources and late cumulate sources enriched in potassium, rare-earth-elements, phosphorus and associated incompatible elements (KREEP) within the lunar mantle. The Apollo 14 green glasses seem to be a product of this mixing, due to their relatively high concentrations of both Th and Sm

2. The Th abundances in the volcanic glasses can be used to infer the U and K values of the glasses due to known relationships between Th and U (Th/U = 3.7) and U and K (K/U = 3200) on the Moon. Since the glasses represent near primary melts from the

lunar mantle, the glass compositions can be used to infer the composition of the lunar mantle. Given this information, the amount of heat produced by the decay of radioactive elements (e.g. Th, U, and K) in the lunar mantle can be calculated. Our calculations show that up to 1$\mu W/m^3$ of heat can be produced by the decay of U, Th, and K in the lunar mantle with the Apollo 14 source regions producing the highest values.

3. Comparisons between the Th and Sm abundances in the volcanic glasses and mare basalts show that there is significant overlap. If the volcanic glasses are assumed to be near-primary melts from the lunar mantle and can undergo various degrees of fractional crystallization, it is possible to reproduce the entire range of Th-Sm compositions seen in the mare basalts. This suggests that there is a clear relationship between the mare basalts and specific mantle compositions represented by the volcanic glasses, which allows us to trace the evolution of Th and Sm from the lunar mantle to the lunar surface.

4. Analyses of the Makaopuhi lava lake samples show that as the temperature decreases, the melt composition exhibits a decrease in Ni, Co, and Cr, a minor increase in Mn and V, and substantial increases in K, Y, Sm, and Th. Nickel and Cr decrease from olivine cores to rims, whereas Mn, Co, and V exhibit limited variation from core to rim. The behavior of trace elements between olivine and melt changes systematically with decreasing temperature. The apparent distribution coefficients ($D^{ol/melt}$) for highly incompatible elements such as K, Y, Sm, and Th decrease with decreasing temperature. The $D^{ol/melt}$ for Ni remains the same over much of the temperature range ($D^{ol/melt}$ =15), but increases dramatically at very low temperatures. The $Ds^{ol/melt}$ for Cr, V, Mn, and Co systematically increase with decreasing temperature.

5. In this simple “closed” natural basalt system the trace element record preserved in melt and minerals reflect filter pressing, convective transport, and gravitational settling.

6. In addition to these large-scale system processes, the trace element data also reflect micro-scale processes that clearly indicate mineral-melt interface kinetics. This is particularly important for trace elements with either very high Ds (> 8) or extremely low Ds (<0.1). The mineral-melt interface kinetics also reflect growth rate of the individual phases and diffusion of element in the basaltic melt.

B. Conclusions

C. Tangible Results

1. refereed journal articles published*
2. refereed journal articles in press or submitted*

   Hagerty, J.J., Shearer, C.K., and Vaniman, D.T., (2004) “Thorium and samarium in lunar picritic glasses: Implications for heat production in the lunar mantle,” submitted to *Geochimica et Cosmochimica Acta.*

3. refereed journal articles in preparation*

   Hagerty, J.J., Shearer, C.K., and Vaniman, D. (2004) “Closed system behavior of trace elements during basalt crystallization in the Makaopuhi lava lake, Hawaii” being prepared for submittal to *Geochimica et Cosmochimica Acta.*

4. other publications published**

Hagerty, J.J., Shearer, C.K., and Vaniman, D.T., (2003) The behavior of Thorium in lunar picritic magmas: Implications for the bulk Thorium content of the lunar mantle and lunar heat flow. *34th Lunar and Planetary Science Conference,* CD-ROM # 1784.

Hagerty, J.J., Shearer, C.K., and Vaniman, D. (2003) Closed system behavior of trace elements during basalt crystallization in the Makaopuhi lava lake, Hawaii. *Fall 2003 Conference of the American Geophysical Union.*

Hagerty, J.J., Shearer, C.K., and Vaniman, D. (2004) Closed system behavior of trace elements during basalt crystallization in the Makaopuhi lava lake, Hawaii: A natural laboratory for understanding basaltic magmatism on the terrestrial planets *35th Lunar and Planetary Science Conference,* CD-ROM # 1836.

Hagerty, J.J., Shearer, C.K., and Vaniman, D.T., (2004) Thorium and Sm in lunar pyroclastic glasses: Insights into the composition of the lunar mantle and basaltic magmatism on the Moon. *35th Lunar and Planetary Science Conference,* CD-ROM # 1836.

5. other publications in press or submitted**

Haggerty, J.J. (2004) Deciphering trace element behavior during basaltic magmatism on the Moon through ion microprobe analysis of ancient lunar basalts, lunar volcanic glasses, and a terrestrial analogue. Ph.D. Thesis.

6. other publications in preparation**
7. invited technical presentations***
8. contributed technical presentations***

Poster presentation of the abstract "The behavior of Thorium in lunar picritic magmas: Implications for the bulk Thorium content of the lunar mantle and lunar heat flow," at the 34th Lunar and Planetary Science Conference.

Poster presentation of the abstract "Closed system behavior of trace elements during basalt crystallization in the Makaopuhi lava lake, Hawaii." *Fall 2003 Conference of the American Geophysical Union*

Poster presentation of the abstract "Closed system behavior of trace elements during basalt crystallization in the Makaopuhi lava lake, Hawaii: A natural laboratory for understanding basaltic magmatism on the terrestrial planets" *35th Lunar and Planetary Science Conference*.

Oral presentation of the abstract "Thorium and Sm in lunar pyroclastic glasses: Insights into the composition of the lunar mantle and basaltic magmatism on the Moon." *35th Lunar and Planetary Science Conference.*

9. patent applications submitted**
10. patent applications granted**

D. Intangible Results

1. new capabilities

a. Developed ability to analyze small samples for very low concentrations of Th (100 ppb).

2. collaborations & contacts
    a. David Vaniman came to UNM to work in conjunction with Charles Shearer and Justin Hagerty on SIMS analyses of the lunar volcanic glasses.
    b. Charles Shearer and Justin Hagerty traveled to LANL to discuss remote sensing data with David Vaniman and David Lawrence and discussed thermal modeling with Dr. Peter Lichtner.
    c. Visits to LANL to discuss roles of LANL in future Moon and Mars exploration and New Mexico sample receiving laboratory for 2013 Mars sample return mission.
    d. Initial discussions with regards to a joint national ion microprobe facility in New Mexico.
    e. Justin Hagerty currently residing in LANL as a post-doc exploring the use of remote sensing of planetary surfaces to better understand planetary interiors.